proj: HIF-NTX
Electron Beam Diagnostics
title: Chicane Magnet Design Calculations

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1. Requirements:

1. Provide a vertical scan (translation) of a 5 keV (max) E-beam over an 8 cm (+/- 4.0 cm) range.
2. Low cost implementation.
3. Compatible with high vacuum.

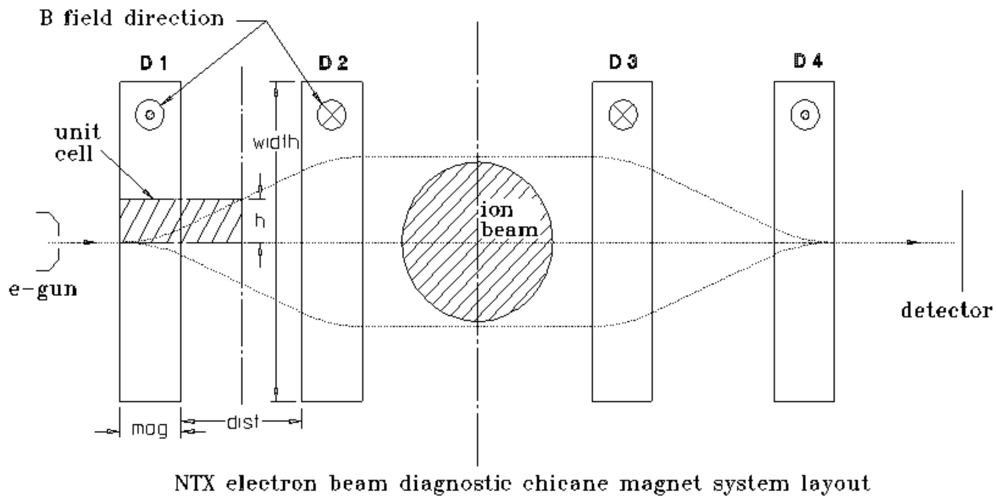


Fig. 1

2. Magnet Description

Proposed is a system of four identical compact iron-dominated DC resistive H-magnets to provide good field uniformity with minimum stray field and to minimize current requirements. They are used inside the vacuum to avoid the need to build a special vacuum chamber to fit between the pole tips. A low number of turns is used to minimize voltage drop and coil surface area, and to help minimize current density for reduced power consumption and cooling requirements. H-coils are machined or wire EDMed from a single block of aluminum, slotted to provide the desired current path, then hard anodized for electrical insulation. This minimizes coil surface area and eliminates organic insulating materials which minimizes outgassing in vacuum. The inorganic insulation may be more resistant to damage from stray electrons. Low power consumption allows cooling to be done by radiation alone, eliminating costly coolant-in-vacuum provisions. The elimination of any winding operations reduces R&D and tooling costs. Steel yokes will have integral pole pieces. Use of annealed vacuum melted ultra low carbon iron is recommended, for high permeability and low outgassing. Flash nickel plating of yoke pieces may help reduce outgassing from corrosion. The design is shown below in several views, and is detailed in LBNL drawing numbers 10R7003, 10R7012, and 10R7023 :

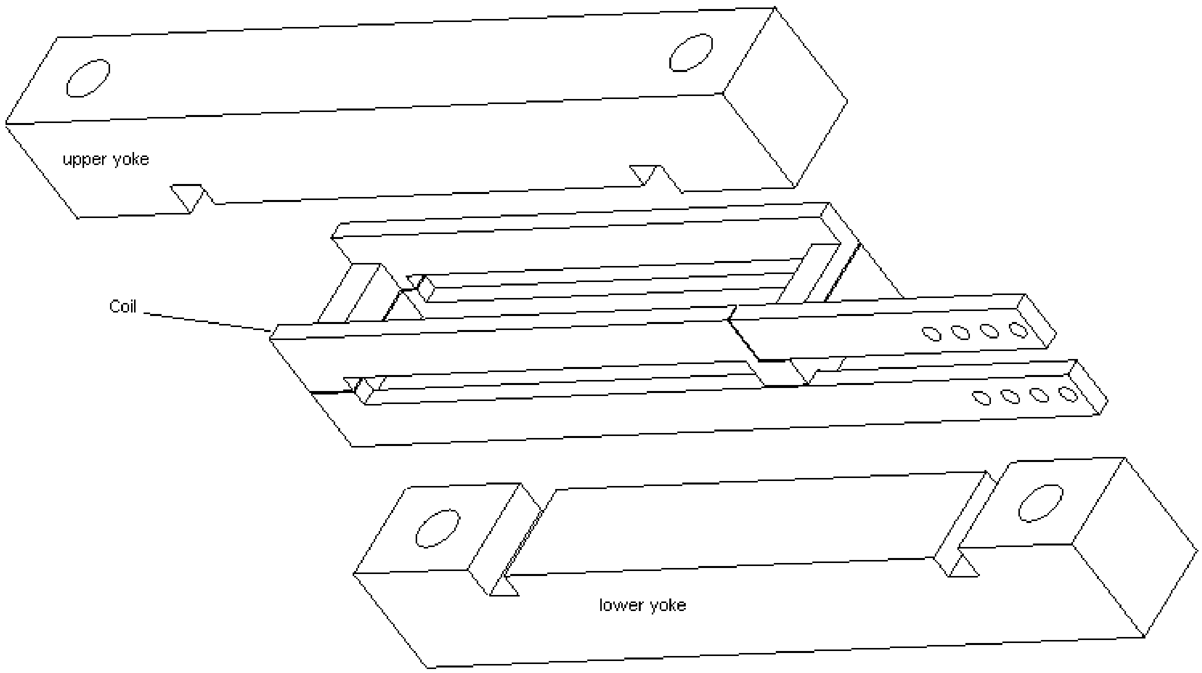


Fig. 2 Exploded view of chicane magnet (yoke bolts not shown)

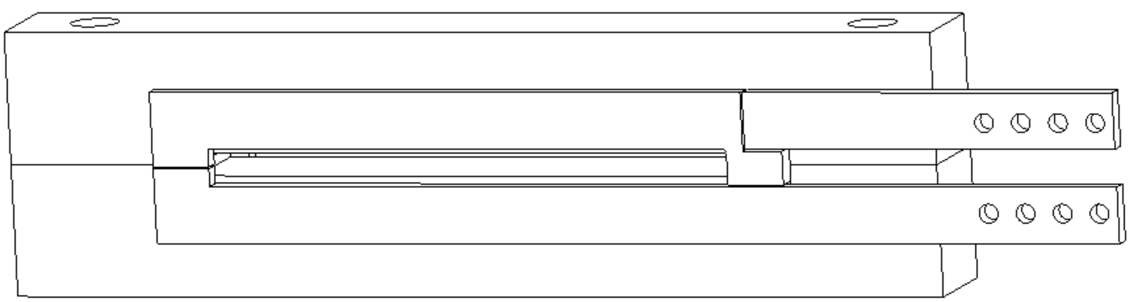


Fig. 3 Assembled view of chicane magnet (yoke bolts not shown)

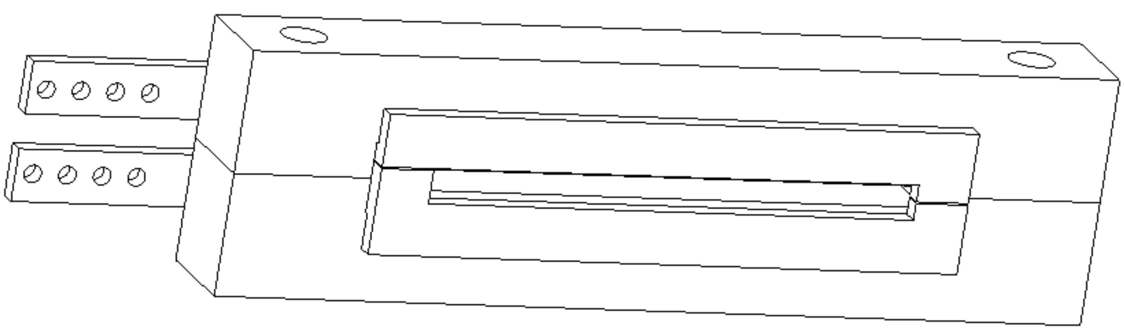


Fig. 4 Backside view of chicane magnet (yoke bolts not shown)

4. Given parameters (see fig. 1):

Beam energy E, maximum

$E := 5000$ eV

Half height of beam, h:

$h := 2.0\text{cm}$

Magnetic length, in horizontal direction, mag:

$mag := 3.0\text{cm}$

Drift distance in horizontal transverse direction, dist:

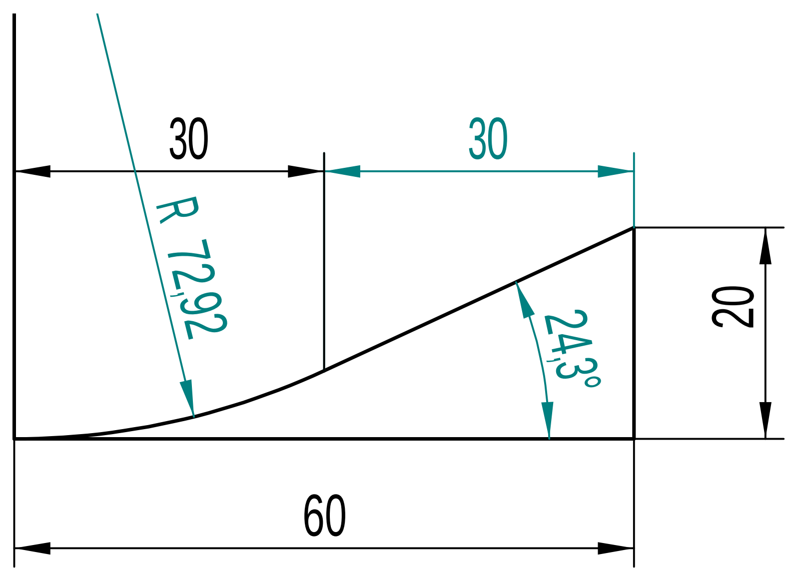
$dist := 6.0\text{cm}$

Magnet width, full, (vertically transverse to e-beam):

$width := 15\text{cm}$

The beam makes an S-shaped path through each half of the magnet system, with a drift section in the middle. The magnets are arranged symmetrically about the ion beam axis, and all four magnets are connected in series to provide "one knob" operation. Thus, all bends and drifts are identical. Shown below is a single bend plus one half of a drift section which make up the essential unit cell of geometry. The half height of the beam is set to the maximum required. Setting the magnetic length then determines the required bending radius and thusly the B field required (sketch units in mm):

$\begin{pmatrix} radius \\ drift \end{pmatrix} :=$



$(h \quad dist \quad mag)$

5. Magnetic Field Required, B:

$radius = 0.0729\,\text{m}$

$B := \frac{3.37 \cdot \sqrt{E}}{radius} \cdot \text{cm}$ $\quad B = 32.681$ G $\qquad$ ref. 1 (cm added to cancel sketch units)

in Tesla: $B_T := B \cdot .0001 \cdot T \qquad B_T = 3.268 \times 10^{-3}\,T$

Magnet gap, g (determined by tolerance for e-beam misalignment):

$g := .006m$

$\mu_0 := 4\cdot\pi\cdot 10^{-7}\cdot\frac{newton}{amp^2}$

$\eta := .961$ magnet efficiency (derived from PANDIRA field analysis, sec 9)

$\xi := 1.259$ bonus fringe field factor (derived from PANDIRA field analysis, sec 9)

$\lambda := \frac{\sec(24.7deg) + 1}{2}$ $\lambda = 1.05$ beam angle factor for fringe field (one side only per magnet)

Number of turns in coil, N:

$N := 2$

6. Current required, I:

$I := \frac{B\cdot g}{\eta\cdot\xi\cdot\lambda\cdot N\cdot\mu_0}\cdot G$ $I = 6.139\,A$

$\rho := 2.5\cdot 1.67\cdot 10^{-8}\Omega\cdot m$ aluminum, 40% IACS (6061-T6)

$l := .3m$ length of a single turn

$a := .00007m^2$ cross section area (7mm x 10 mm xsec, avg.)

$R := \frac{\rho\cdot N\cdot l}{a}$ $R = 357.857\,\Omega\cdot 10^{-6}$

Heat generation and voltage:

$P := I^2\cdot R$ $P = 0.013\,W$

$V := I\cdot R$ $V = 0.0022\,V$

7. Stored Energy and Inductance:

$U := \frac{{B_T}^2}{2\cdot\mu_0}\cdot g\cdot mag\cdot width$ $U = 1.147\times 10^{-4}\,J$

$I := 2\frac{U}{I^2}$ $I = 6.088\times 10^{-6}\,H$

8. Temperature rise, steady state (radiation only):

Coil and Chamber emissivities e and shape factor F:

$\varepsilon := 0.05$ (polished aluminum, worst case) $\sigma := 5.67\cdot 10^{-8}\cdot\frac{W}{m^2\cdot K^4}$ (Stefan-Boltzman constant)

$T_2 := 300K$

$F_{12} := 1$

Coil Surface Area, A:

$A := (.01 + .007 + .007)\cdot.15\cdot 4\cdot m^2$ (considering only the exposed coil sections)

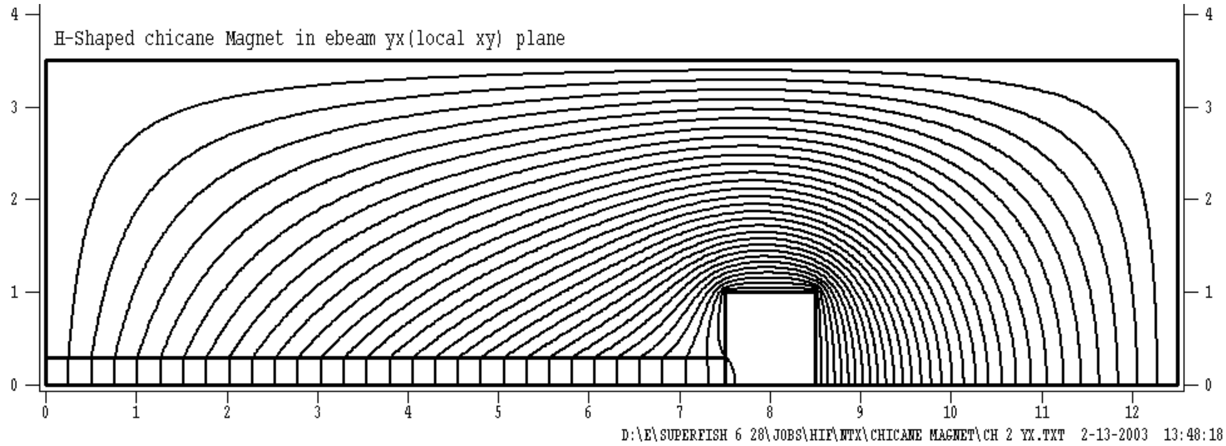
$A = 0.014\,m^2$

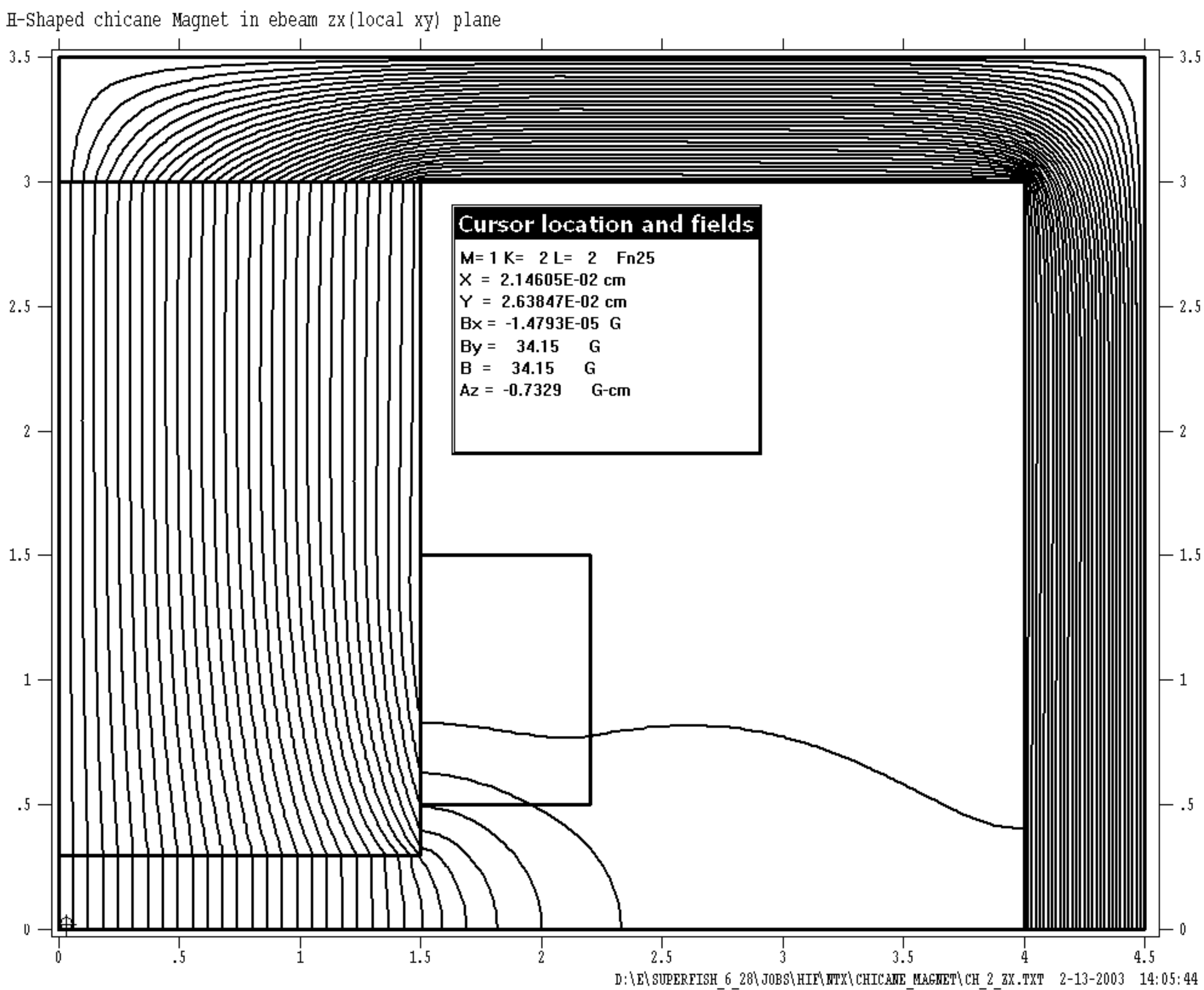
$$\Delta T := \sqrt[4]{\frac{P}{\sigma \cdot A \cdot \varepsilon} + T_2^{\,4}} - T_2$$ (from eq. 8-43a, ref.2)

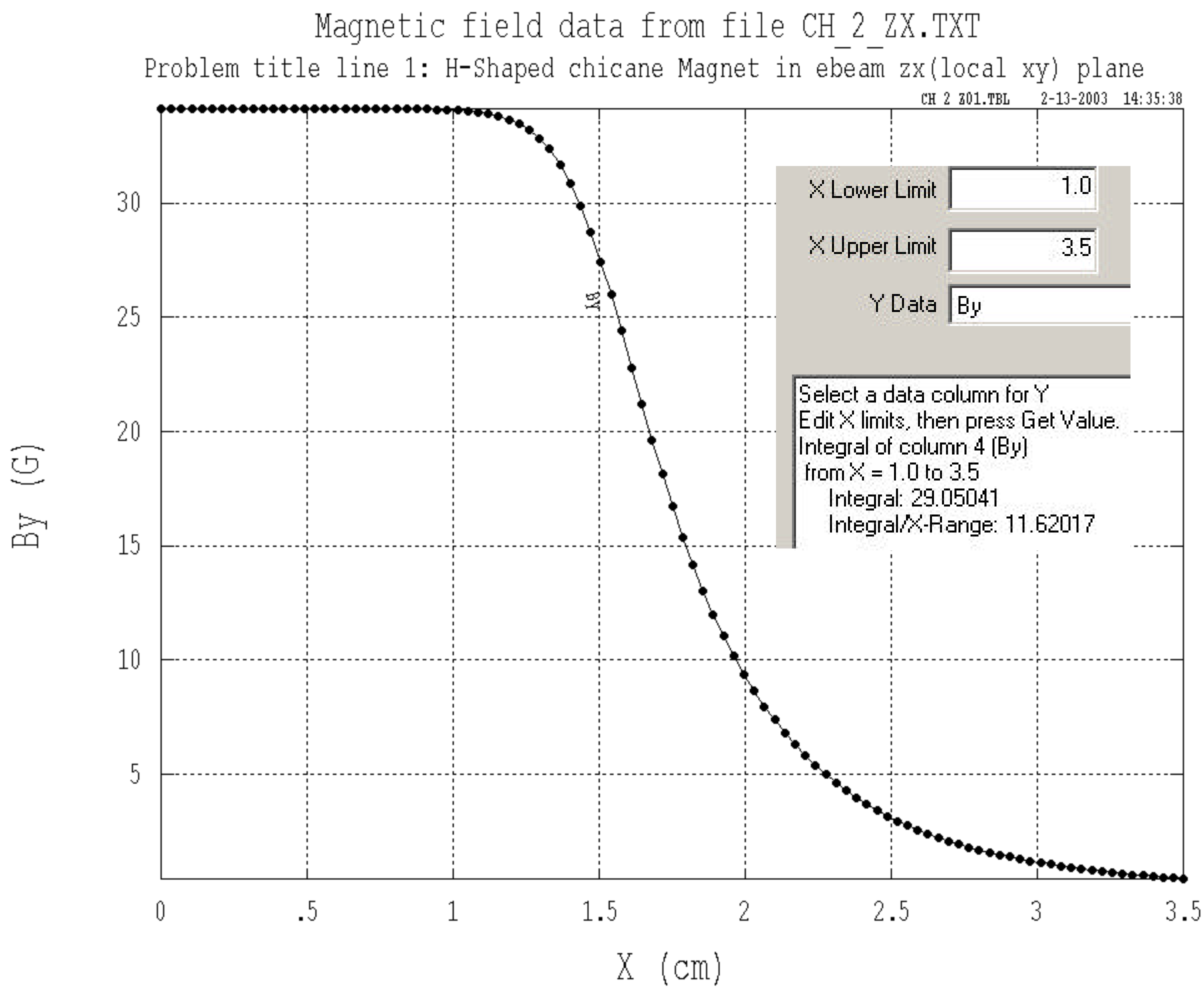
$$\Delta T = 3.0\,K$$

9. PANDIRA Analysis

PANDIRA (ref 3) was used to both verify the basic calculations above and to determine the fringe field which may be important for beams not on the magnet centerline.







one can see that even though the magnet is only (2x)1.5cm long, along the e-beam direction, a substantial "bonus fringe field" extends past the end, providing additional beam bending. This fringe field is integrated from a point 0.5 cm (5/3 x half-gap) in from the edge of the pole, and the result shown in the box. Total integrated $B_y x$, thru the entire magnet is then:

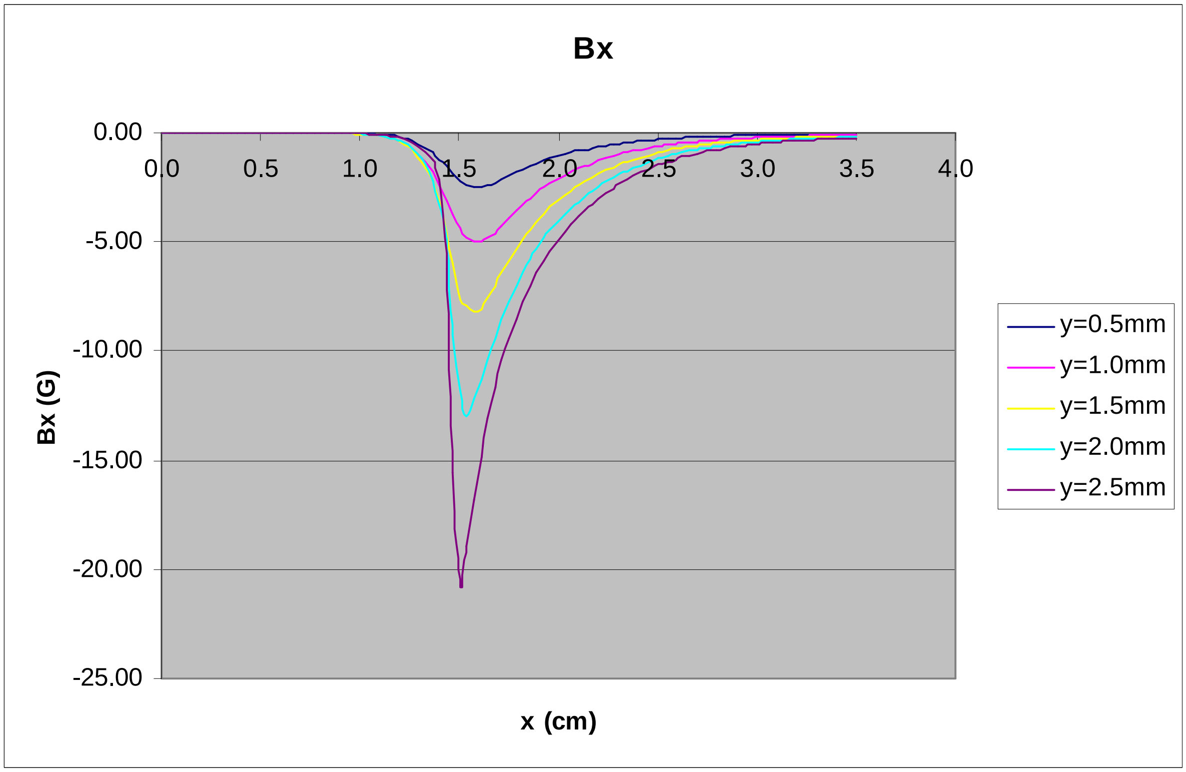
$$B_{yX} := \left(\mathrm{mag} - \frac{5}{3}g\right)\cdot B\cdot G + 2\cdot 29.05 G\cdot cm \qquad B_{yX} = 123.462\, G\cdot cm$$

$$\xi := \frac{B_{yX}}{B\cdot G\cdot \mathrm{mag}} \qquad \xi = 1.259$$

this "bonus fringe field" is used in the calculations above, sec 3

B_x component of Fringe Field:

For missteered beam not passing along on the midplane, or for beam widths with a cross section comparable to the magnet half gap, there could be a transverse mis-steering effect when the beam has a vertical velocity component (in the angled drift region of each magnet pair). This effect is due to the X-component of the fringe field in the region to each side of the midplane which will have a non-zero cross product with the aforementioned vertical velocity (Y) component. The program SF7 was used to generate the B_x field component and (e-beam Z) integrated B_x field along the (e-beam Z) direction for several different values of the (local Y) distance from the midplane: (also the e beam X direction). These are shown below:



$$\int B_x \, dx \quad \begin{aligned} &= -1.69 \text{ G-cm for } y=0.5 \text{ mm} \\ &= -3.37 \text{ G-cm for } y=1.0 \text{ mm} \\ &= -5.03 \text{ G-cm for } y=1.5 \text{ mm} \\ &= -6.76 \text{ G-cm for } y=2.0 \text{ mm} \\ &= -8.65 \text{ G-cm for } y=2.5 \text{ mm} \end{aligned}$$

(for each side of the magnet)

Magnet efficiency, h:

Simulated transfer function F_s:

(from PANDIRA e-beam yx analysis): $B_s := 33.06G \qquad I_s := 2 \cdot 8.213A$

$$F_s := \frac{B_s}{I_s} \qquad F_s = 2.013 \frac{G}{A}$$

Ideal transfer function, F_i:

$$F_i := \frac{\mu_0}{g} \qquad F_i = 2.094 \frac{1}{A} G \qquad \eta := \frac{F_s}{F_i} \qquad \eta = 0.961 \frac{A}{m^2} \frac{m^2}{A}$$

10. References:

1. LBL Design Data #32
2. Holman, J.P. Heat Transfer, 4th ed.
3. POISSON/SUPERFISH, v 6.28, Los Alamos Accelerator Codes Group